

The precursor state to superconductivity in CeIrIn₅: Unusual scaling of magnetotransport

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We present an analysis of the normal-state Hall effect and magnetoresistance in the heavy fermion superconductor CeIrIn₅. It is demonstrated that the modified Kohler's scaling—which relates the magnetoresistance to the Hall angle—breaks down prior to the onset of superconductivity due to the presence of a precursor state to superconductivity in this system. A model-independent, single-parameter scaling of the Hall angle governed solely by this precursor state is observed. Neither the Hall coefficient nor the resistivity exhibit this scaling implying that this precursor state preferentially influences the Hall channel.

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The variety of low temperature electronic ground states observed in heavy fermion systems primarily arises from two competing fundamental physical processes: the Ruderman-Kittel-Kasuya-Yosida interaction favoring magnetic order and the Kondo effect that screens the local moments [1]. Of particular interest are systems in which the magnetic order can be driven to zero temperature. If this takes place in a continuous fashion it is referred to as a Quantum Critical Point (QCP). The often observed existence of unconventional superconductivity in the vicinity of such a QCP has added to the interest in these exotic phase transitions, as it suggests that Cooper pair formation could be governed by the presence of (antiferro-) magnetic fluctuations [2]. The Ce-115 systems (of the form CeMIn₅, with $M = \text{Co, Ir, or Rh}$) have proven to be an interesting playground where manifestations of these intrinsic energy scales are unambiguously observed [3]. For instance, in the ambient pressure superconductor CeCoIn₅, the QCP can be approached with applied magnetic fields of the order of the superconducting upper critical field $H_{c2}(0)$ [4]. The antiferromagnetic order observed in CeRhIn₅ can be suppressed by applying pressure of the order of 1.6 GPa which, again, results in a superconducting ground state [5]. In CeIrIn₅, though the superconducting regime is reasonably separated from the (possibly metamagnetic) QCP [6], signatures of the presence of antiferromagnetic fluctuations in the vicinity of superconductivity have been observed [7]. Besides unconventional superconductivity, experimental signatures such as the presence of line nodes in the superconducting gap structure [8] and anomalous magnetotransport have also brought into focus the remarkable similarities which these systems share with the high temperature superconducting cuprates [9].

One of the outstanding puzzles presented by these complex materials is the changing low energy excitations of the normal state just prior to the formation of the superconducting state. In the cuprates for instance, it is

now understood that superconductivity is preceded by the opening of a *pseudogap* in the electronic density of states [10]. Typically, this state is associated with experimental signatures like a deviation from the linear temperature dependence of resistivity [11] or a decrease in the spin-lattice relaxation rate ($1/T_1$) in nuclear magnetic resonance measurements [12], and is now considered an intrinsic energy scale of these systems. Recently, experiments have indicated that a precursor state to superconductivity may also exist in the Ce based heavy fermion metals. The Ce-115 systems have been exemplary in this aspect, with the presence of such a precursor state being inferred from measurements like resistivity [13], nuclear quadrupole resonance [14], the Hall angle [15] and the Nernst effect [16]. In this Letter, we report on the analysis of the normal-state magnetotransport data in CeIrIn₅. To this end, prior [15] and new simultaneous measurements of isothermal Hall effect and magnetoresistance in magnetic fields $\mu_0 H \leq 15$ T and in the temperature range $0.05 \text{ K} < T < 2.5 \text{ K}$ on high-quality single crystals are evaluated. We demonstrate that the modified Kohler's scaling—relating the magnetoresistance to the Hall angle—breaks down prior to the onset of superconductivity due to a change in the Hall scattering rate. Moreover, the critical field $H^*(T)$ of the precursor state to superconductivity alone has been used to scale the temperature- and field-dependent Hall angle $\theta_H = \cot^{-1}(\rho_{xx}/\rho_{xy})$. The fact that a similar scaling procedure fails for the individual properties, i.e., the resistivity ρ_{xx} and the Hall coefficient $R_H = \rho_{xy}/\mu_0 H$, suggests that this precursor state preferentially affects the Hall channel.

Fig. 1(a) depicts the isothermal Hall coefficient $|R_H|$ as a function of applied field H for different temperatures. The sharp drop in $|R_H|$ corresponds to the onset of superconductivity. The magnetic field dependence of the transverse resistivity ρ_{xx} is plotted in Fig. 1(b). Besides the onset of superconductivity, a crossover in the sign

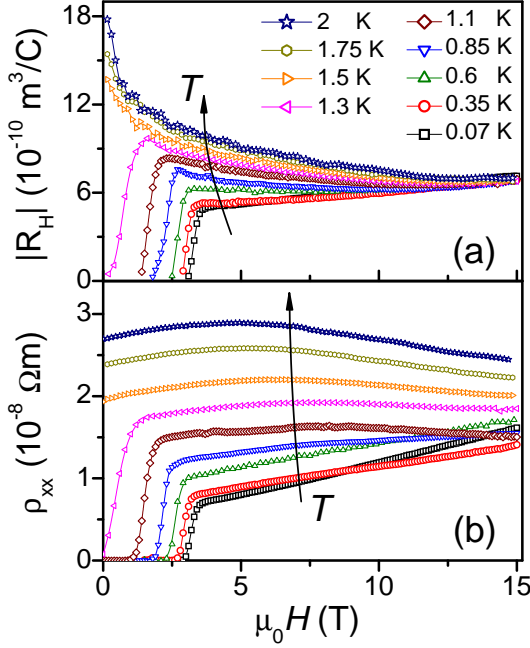


FIG. 1: Magnetic field dependence of (a) the Hall coefficient $|R_H|$ and (b) the resistivity ρ_{xx} measured at selected temperatures. The sharp drop corresponds to the onset of superconductivity.

of the magnetoresistance corresponding to the onset of a coherent Kondo state is visible in the high-temperature data sets. Though this crossover from an incoherent to a coherent Kondo scattering regime is a characteristic feature of the heavy fermion metals, many similarities in the normal state magnetotransport of the superconducting cuprates and the Ce-115 systems have recently come to light. For instance, the resistivity ρ_{xx} has a linear temperature dependence, the Hall coefficient R_H varies approximately as $1/T$, and the Hall angle follows a $\cot \theta_H \propto T^2$ dependence in these conceptually different classes of materials. In the cuprates, theoretical support for these experimental observations have relied on the rather extraordinary idea that, in contrast to conventional metals, the transverse Hall scattering rate (τ_H^{-1}) in the cuprate metals is a distinct entity as compared to the transport scattering rate (τ_{tr}^{-1}) [17, 18]. Since the resistivity is governed by τ_{tr}^{-1} and R_H by the ratio τ_H/τ_{tr} , it follows that $\cot \theta_H$ is a manifestation of the transverse relaxation rate τ_H^{-1} alone. In conventional metals (with an isotropic single scattering rate), the magnetoresistance $(\rho_{xx}(H) - \rho_{xx}(0))/\rho_{xx}(0)$ arising due to the orbital motion of charge carriers is known to scale as a function of $H/\rho_{xx}(0)$ (Kohler's rule [19]). A natural consequence of the presence of two scattering rates was the re-formulation of this scaling rule to relate the transverse magnetoresistance with the Hall angle [20]. This scaling of the form $(\Delta\rho_{xx}/\rho_{xx}(0)) \propto \tan^2 \theta_H$ has been successfully applied to magnetotransport data in both

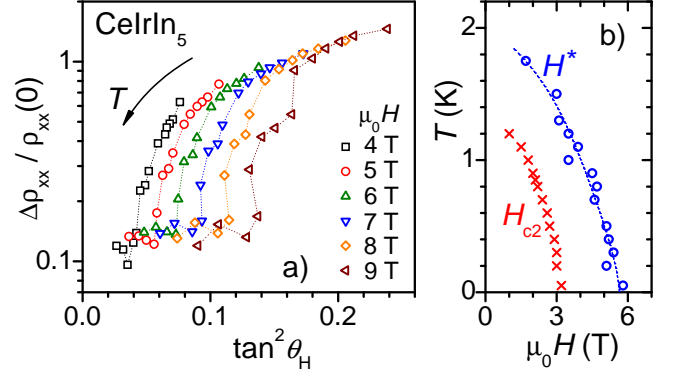


FIG. 2: (a) Magnetoresistance vs. squared tangent of the Hall angle θ_H revealing strong deviations from the modified Kohler's rule. Here, temperature is an implicit parameter as indicated. (b) Part of the $H-T$ phase diagram of CeIrIn_5 exhibiting the boundary of superconductivity and its precursor state (marked by H_{c2} and H^* , respectively).

the cuprates as well as in all the Ce-115 compounds. In CeIrIn_5 for instance, it was recently demonstrated that this scaling works in a wide temperature range down to about 2 K [21], but this study did neither extend down to the precursor nor the superconducting regime [cf. Fig. 2(b)]. The vital question remained whether the superconducting condensate emerges from within the phase space where this scaling is obeyed. Fig. 2(a) exhibits the modified Kohler's scaling as determined from our new magnetotransport data. Clearly, the scaling procedure mentioned above is *not* applicable down to the lowest accessible temperatures. This observation is in line with the inference that the formation of the superconducting condensate in CeIrIn_5 is preceded by a precursor state as determined by a change in the Hall mobility.

In the heavy fermion metals, the crystal electric field and the single ion Kondo effect provide two fundamental energy scales that crucially influence its physical properties. An additional energy scale of importance [22, 23] is related to the intersite coupling between the local moments due to the Ruderman-Kittel-Kasuya-Yosida interaction. In this context, it is important to clarify whether this precursor state to superconductivity in CeIrIn_5 represents an intrinsic energy scale of the system, and to discern the manner in which it influences the normal-state magnetotransport. One powerful tool of identifying intrinsic energy scales in strongly correlated systems is the quest for universal trends of, and relationships between, measured physical quantities. In the heavy fermion systems, early attempts to scale physical properties using a single energy scaling parameter met with only limited success [24]. However, in the cuprates it has been demonstrated [25, 26, 27] that a single-parameter scaling of experimental data was possible by using the energy scale of the pseudogap alone. By normalizing any measured electrical or thermal transport quantity $f(x)$

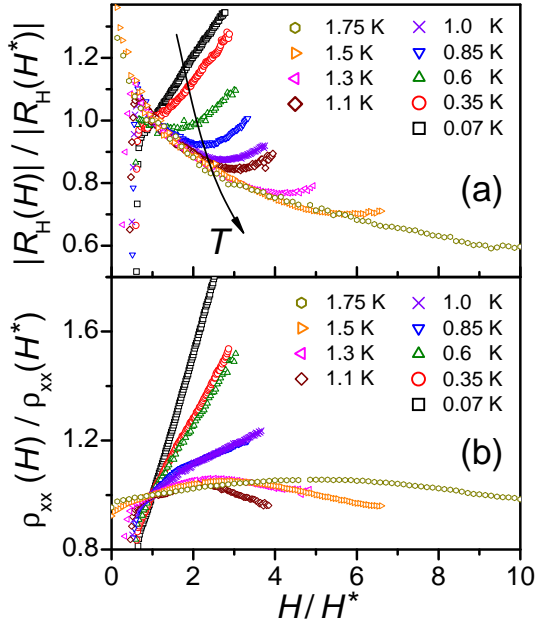


FIG. 3: (a) The scaled field dependences of the the normalized Hall coefficient $|R_H(H)|/|R_H(H^*)|$ and (b) the normalized resistance $\rho_{xx}(H)/\rho_{xx}(H^*)$ plotted as a function of the normalised field (H/H^*) for CeIrIn₅.

along with its variable x by the corresponding values at the onset of the pseudogap [$f(x^*)$ and (x^*) , respectively] the measured data could be made to collapse into a single universal curve. Thus, the scaling is of the form $f(x)/f(x^*) \propto F(x/x^*)$. Consequently, the normalized Hall coefficient ($|R_H(H)|/|R_H(H^*)|$) is plotted as a function of normalized field (H/H^*) for CeIrIn₅ in Fig. 3(a). Here, the values H^* [Fig. 2(b)] were determined earlier from the change in the Hall mobility [15]. Fig. 3(b) shows the equivalent scaling for the magnetoresistance, i.e. $\rho_{xx}(H)/\rho_{xx}(H^*)$ as a function of H/H^* . Interestingly, neither $R_H(H)$ nor $\rho_{xx}(H)$ scale onto a universal curve implying that both of these quantities have significant contributions which are not scaling-invariant.

A priori, there is no simple explanation of the nature of these *non*-scaling-invariant contributions to R_H and ρ_{xx} . One possibility which cannot be ruled out is the influence of disorder in these systems, with impurity scattering not being scaling-invariant. This problem can be circumvented by the analysis of the Hall angle. From prior work on the cuprates it is known that the cotangent of the Hall angle (which is directly related to the charge carrier mobility) is a quantity of basic interest [18]. It has been shown that $\cot \theta_H$ follows a T^2 dependence, independent of the extent of impurity substitution as well as the charge carrier density [28]. This relative insensitivity of $\cot \theta_H$ to material properties (which is related to the fact that it does *not* depend on τ_{tr}) has led to the conjecture that it is an even more fundamental property than R_H . Moreover, deviations from $\cot \theta_H \propto T^2$ have

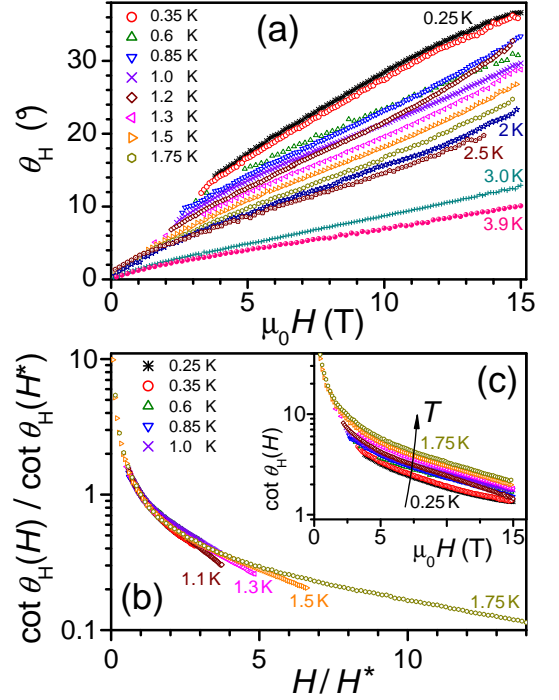


FIG. 4: (a) Field dependence of the Hall angle θ_H . (b) Scaling of both $\cot \theta_H$ and field H with respect to H^* reveals a collapse of the data into a single generic curve. The inset (c) shows the field dependence of some unscaled data sets.

been used to identify the onset of the pseudogap state in the cuprates [29]. Fig. 4(a) presents the isotherms of the field dependent Hall angle as measured in CeIrIn₅, indicating that θ_H is quasi-linear as a function of H . If the different electronic states in CeIrIn₅ are manifestations of a change in the geometry of the Fermi surface, this should be visible in the field dependence of the Hall angle which measures the effective deflection of charge carriers in the material by the applied magnetic field. However, the lack of any observable features at fixed values of θ_H suggests that there is no abrupt change in the geometry of the Fermi surface, at least in the range of our measurements. Here, it is emphasized that θ_H attains a value of more than 30° at large fields which is substantially larger than what is commonly observed in the cuprates. In line with the earlier analysis, the normalized Hall angle $\cot \theta_H(H)/\cot \theta_H(H^*)$ is plotted as a function of normalized field H/H^* in Fig. 4(b). For comparison, the unscaled data are shown in the inset Fig. 4(c). Only in the former case a good scaling behavior is obtained, an observation which is remarkable in view of the fact that such a scaling procedure was found to be ineffective for both $\rho_{xx}(H)$ and $R_H(H)$, Fig. 3. This scaling of $\cot \theta_H$ unambiguously implies that the precursor state observed in CeIrIn₅ represents an intrinsic energy scale of the system which influences the magnetotransport in a substantial region of the field-temperature phase space. Note that the scaling of the critical field $H^*(T)$

of the precursor state with the superconducting critical field $H_{c2}(T)$ suggests that they may arise from the same underlying mechanism [15]. This provides a natural link between the normal-state properties of CeIrIn₅ and the superconductivity in this system.

The fact that scaling is observed in $\cot\theta_H$ clearly suggests that the precursor state is primarily associated with the transverse Hall scattering rate τ_H^{-1} . However, it would be erroneous to conclude that the precursor state is associated *only* with τ_H^{-1} , since this state is also identified by a subtle feature in the magnetoresistance [15]. Nevertheless, the lack of scaling in both ρ_{xx} and R_H suggests that the magnetic field seemingly influences τ_H^{-1} preferentially as compared to τ_{tr}^{-1} . Interestingly, this is also in agreement with prior results on underdoped cuprates where it was suggested that the formation of a pseudogap primarily affects the Hall channel, and has little effect on the diagonal conductivity [30]. Moreover, the observation of scaling *only* in $\cot\theta_H$ re-emphasizes the presence of two distinct scattering processes which selectively influence the resistivity and the Hall angle in this heavy fermion metal. The observed anisotropy in the magnetic field response of the scattering rates may arise as a consequence of coupling of the quasiparticles to incipient antiferromagnetic fluctuations [31, 32]. Such a coupling might then renormalize the scattering rates along different directions of the Fermi surface. There exists a body of work to imply that this might indeed be the case in the Ce-115 systems. For instance, investigations of the angular-dependent resistivity in CeCoIn₅ have indicated the presence of two distinct regimes in their magnetic field dependences, separated by a critical angle θ_c , which in turn is governed by the intrinsic anisotropy [33]. Moreover, recent thermal conductivity measurements indicated that the superconducting gap of CeIrIn₅ may have a $d_{x^2-y^2}$ symmetry: a signature that the superconductivity is strongly influenced by the presence of antiferromagnetic fluctuations [34]. These fluctuations are themselves inferred to be anisotropic in nature, with the magnetic correlation length along the basal plane being larger than along the c axis, $\xi_{ab} > \xi_c$ [7]. The two corresponding scattering rates appear to be influenced by the low-lying precursor state in a disparate fashion. In CeIrIn₅, it has been observed that $\cot\theta_H$ increases anomalously in the precursor state [15]. Since $\cot\theta_H = 1/\omega_c\tau_H$ this suggests that τ_H^{-1} is *enhanced* in the precursor state—provided, of course, that the effective mass m^* remains constant. This is in contrast to observations in the cuprates as well as in the related system CeCoIn₅ [13], where it was found that τ_{tr}^{-1} *reduces* at the onset of the precursor state.

In summary, the analysis of the normal-state magnetotransport in CeIrIn₅ reveals that the modified Kohler's plot (relating the magnetoresistance to the Hall angle) breaks down prior to the onset of superconductivity, presumably due to the presence of a precursor state to su-

perconductivity in this regime of the H - T phase space. Moreover, the Hall angle obeys a single-parameter scaling unambiguously governed by this precursor state. The absence of scaling in R_H and ρ_{xx} is clearly indicative of the presence of two distinct scattering times, in similarity with observations in the cuprate superconductors. This could very possibly be a generic feature of many heavy fermion superconductors. The fact that *only* the Hall angle is scaled by the precursor state also implies that this state preferentially influences the Hall channel and has a relatively weaker influence on the resistivity. It is imperative to map the evolution and symmetry of both the superconducting as well as the precursor state by more direct probes, e.g., in order to formulate a theoretical basis for the observed phenomena.

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